THE DESIGN AND DEVELOPMENT OF A ROBOTICALLY EMPLACED HAND PACKED SHAPED CHARGE

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ABSTRACT

The recent use of buried Improvised Explosive Devices (IEDs) has resulted in a high cost to the U.S. Army, in terms of both lives and materiel lost in the South West Asian (SWA) theater. The safe destruction of these types of devices is currently the responsibility of explosive ordnance disposal (EOD) operators. In an attempt to make a dangerous job safer, U.S. Army EOD personnel are increasingly using robots to emplace charges that can destroy deeply buried ordnance. In an attempt to destroy these deeply buried IEDs, ARDEC EOD and Energetics, Warheads, and Environmental Technology (EWET) personnel teamed to develop a high performance anti-IED shaped charge. This was a problem for which, at least up to this point, there had been no dedicated solution. Due to the urgent need to field such a device, any potential solution would be required to be loaded locally in theater in order to preclude complications associated with the normal acquisition process. In addition, any solution would have to be capable of being deployed via a remotely controlled robot. The efforts contained within this paper were conducted over an 8 month time period from the beginning of the first test to the time that the units were actually deployed to the theater of operation.

1. INTRODUCTION

Unexploded ordnance (UXO) and IEDs pose a serious threat to civilians and military personnel in various theaters around the world. These same devices however, pose a much more serious threat to the EOD personnel assigned the task of destroying them. In an effort to make the job of destroying UXO and IEDs safer, Picatinny Arsenal EWET and EOD personnel teamed together to develop, test, and field a hand packed, robotically emplaced, shaped charge capable of defeating buried UXO and IEDs. The conditions under which IEDs are being encountered in the field in Iraq, often deeply buried under a soil and asphalt overburden, necessitated a higher performance device than any previously developed and currently in use for this purpose. This new device, loaded in the field with C-4 and capable of being detonated with a standard high output blasting cap via shock tube, was designed to penetrate and detonate buried IEDs. While the type of ordnance used in IEDs varies, one of the more difficult pieces of munition commonly encountered is the former Soviet 152mm artillery projectile. This projectile is known for having a thick case that is difficult for a shaped charge to penetrate when deeply buried beneath soil and asphalt. A series of tests were conducted to determine the suitability of various sizes of shaped charges, fired at various standoff distances, through different amounts of soil, asphalt, and steel overburden, to design a shaped charge that would safely detonate buried ordnance.

2. INITIAL TESTING

Upon beginning the program, the user's primary requirement was that any new shaped charge design must be capable of penetrating a layer of asphalt and rocky soil before impacting and destroying a buried IED. It was the experience of EOD operators recently returned from the SWA theater, that was the type of overburden under which IEDs were commonly found. As a result of this rather vague criterion however, a couple of sizes of shaped charge devices needed to be initially tested.

In addition to the penetration requirement however, a very real requirement which shaped the final geometry of this design was the need to be able to place the charge via remote controlled robot. Due to the extremely hazardous nature of IED location and disposal, especially in scenarios commonly encountered in Iraq, remotely controlled robots are being used with increasing frequency to provide a safe standoff distance from which EOD operators can still go about the business of destroying UXO and IEDs. While this tremendously reduces the risk posed to EOD operators, the complication that arises is that any device used by the robot must be capable of being manipulated with significantly less dexterity, within appreciably constrained ranges of motion and articulation, than would be capable if it were hand emplaced by a human. In addition, weight constraints were placed on the warhead as the robotic manipulator was only capable of manipulating and emplacing a relatively light weight charge. These design requirements, while by no means insurmountable, manifested themselves in various fea-

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tures of the final product that are discussed later in further detail.

Both items were developed to be hand loaded with the malleable explosive composition C-4. Although C-4 isn't as high performance as many pressed explosives more commonly used in shaped charges, it is readily available, used by EOD personnel on a daily basis, and has a known track record of being able to satisfactorily drive shaped charge liners. Furthermore, due to the fact that IEDs were being encountered on an almost daily basis, a solution was needed quickly. The fielding of a low technology copper lined shaped charge that could be locally loaded with explosive, rather than loaded at a loading plant and shipped in theater, would circumvent much of the traditional time consuming procedures required for the acquisition of typical ordnance, thus decreasing the time that the user was in the field without a solution. It was in the interest of expediency, familiarity, and availability that both sizes of rounds were designed to accept standard high output blasting caps that EOD personnel commonly use.

The sizes of the shaped charge designs chosen for initial testing were 81 and 66 mm in diameter. Copper was chosen as the liner material as decent numbers of both liners had already been manufactured and were available in this material. The 81 mm diameter liners were previously developed for generic insensitive munitions testing while the 66 mm diameter liners had been developed for a previously designed shoulder fired light anti-tank weapon (LAW) that never entered production. The bodies for each item were locally manufactured out of aluminum. The tops, the primary function of which was to hold the detonator, were also locally manufactured out of either aluminum or acrylic. Figure 1 shows unloaded rounds of both sizes.

Figure 1 Unloaded 81 mm and 66mm prototypes

As previously mentioned, in the interest of expediency and availability, both rounds were designed such that they could be loaded with Composition C-4 in the field at the time of use. This was accomplished by inserting the conical liner into the body, screwing down the liner retaining ring, and then stuffing the C-4 in the back side around the liner but in the space contained by the body. Since the liner to explosive interface is the most critical factor in shaped charge performance, extra care was taken to ensure the C-4 was properly inserted into the body and that it was in intimate contact with the liner. The technique which was found to produce the fewest gaps between the liner and explosive was to break off small pieces of C-4 from the larger blocks and then to knead them until they became soft at which point they were pressed around the liner by hand. Figure 2 shows prototypes of a partially loaded 81mm charge and a completely loaded 66mm charge ready for firing.

Figure 2 Partially loaded 81mm and 66mm prototypes

Both sizes of rounds were tested against overburden representative of that seen by EOD operators who had recently returned from in theater. It was hoped that at least one of the two rounds would be able to successfully penetrate the asphalt and rocky soil while still maintaining enough energy to penetrate a steel target below. Since the precise orientation and geometry of buried IEDs could not be ascertained a priori, buried target plates were used under the overburden for three out of four of the initial shots. An empty 105mm projectile was used as the target for the fourth and final test shot. Standoff distances of both 1 and 3 charge diameters (CDs) were used to ensure that a sufficient range of penetration capability would be tested. From the extensive body of work in the field of traditional anti-armor applications of shaped charges performance is well known to be a strong function of standoff distances. The reason for this is that given too little standoff, the jet has not had adequate time to form and to stretch to the maximum extent possible before being interfered with by the target. At distances that are too great, the charge has more than enough time to form and to stretch and in fact begins to particulate. When particulation occurs, the particles that form begin to drift off course and penetration drops off appreciably. The effect is that penetration is generally maximized at

stand off distances greater than 3 charge diameters depending on the specific liner design. Figure 2 depicts both the small and large charges at various charge diameters of standoff.

Figure 3 81mm charge at 3 CDs of standoff and 66 mm charge at 1 CD of standoff

While the penetration results were less precise than those commonly seen for dedicated anti-armor warheads, overall penetration depth was more than sufficient for the intended application. The lack of precision is seen in the irregular shape of the penetration hole. In the initial round of testing key holes were often formed, probably as a result of gaps between the explosive and the liner interface that occurred during loading. An example of the irregular shaped penetration hole can be seen below in figure 4.

Figure 4 Typical penetration results

In all cases, penetration was greater than required. In the fourth and final shot, conducted against an empty 105mm projectile, the shaped charge jet penetrated through both sides of the round and into the ground beneath as seen in figure 5.

Figure 5 Initial larger design tested against an empty 105mm projectile

Since the smaller of the two shaped charges penetrated a sufficient depth of steel, at a single CD of standoff and through a representative level of overburden, it was down selected for further development. Although the longer standoff resulted in deeper penetration, it would also force the device to be much less stable and difficult to deploy via remote controlled robot. In addition, the smaller charge required a much smaller amount of C-4. This would make it at least somewhat more convenient to use in the field since less C-4 could be carried to be used with each of the smaller charges.

Larger diameter charges would certainly have resulted in even greater penetration but the ultimate diameter was limited by the extent to which the robotic hand could open as well as by how much it could lift. As it turned out however, the penetration exhibited by the smaller of the two charges was more than sufficient for the level of overburden found on commonly encountered buried IEDs.

3. SUBSEQUENT TESTING

After the initial round of testing, wherein it was determined that penetration performance should be great enough for the 66mm charge at 1 CD of standoff, a test was conducted against actual live 155 mm M107 artillery projectiles loaded with Composition B. Two 66mm shaped charge bodies were manufactured and loaded with C-4 explosive. A setup of the initial IED simulant and the overburden setup can be seen in figure 6 below.

Figure 6 Second round test against live IED simulant

In addition to the asphalt and rocky soil, a thick steel plate was placed on top of the round in the region that the jet would penetrate. This was done to simulate a scenario that would be more difficult for the shaped charge to penetrate than it would ever likely see during its use in theater. It was an over test conducted in an attempt to prove that any scenario which would be encountered in the field would be capable of being defeated. The results of the first test were a high order detonation with no large fragments remaining in the immediate vicinity.

The second of the two tests was designed to test the shaped charge to an even greater extent and as a result, even more asphalt, dirt, and intervening steel were used before the M107 artillery projectile. The results of this test were somewhat different in that there was an indication of a low order detonation. Evidence of this could be found in the large fragments and pieces of unreacted high explosive (HE). Although this was not a high order detonation reaction, as was seen after the previous test, it was judged to be more than satisfactory as any IED that exhibited a similar reaction could reasonably be assumed to be inoperable or at least rendered safe by virtue of destruction of any firing mechanism. Evidence of the low order reaction, due to excessive overburden, can be seen in figure 7.

Figure 7 Large base fragment with unreacted Composition B

After the second round of testing demonstrated that the 66 mm charges would successfully detonate buried IEDs, a third round of testing was conducted with locally fabricated bodies. This batch of bodies was fabricated on EOD's Stereo Lithography Apparatus (SLA) machine and allowed the users to make a prototype and incorporate design features that they thought of while using inert shaped charged simulators with the robotic manipulator. For example, one of the operators decided that in order to lay the shaped charge on its side, to potentially attack an IED from the side or to be emplace the device on a slope, a square top would conveniently stop the device from rolling. Additionally, warheads development personnel felt that a more stable platform would be provided if the 1 CD of standoff were built into the body. This would make the round more stable than it would be if it had to be mated to a stand in order to provide the correct standoff distance. These design features might not otherwise have been incorporated into the final design if EOD personnel had not had the SLA machine on which to rapidly design and incorporate beneficial features discovered during testing.

In the interest of ensuring that none of their changes affected the penetration performance of the shaped charges, 4 bodies were printed and tested against steel to ensure equivalent performance. Figure 8 shows both a partially loaded body and the final configuration as set up on the asphalt overburden and witness plate beneath.

Figure 8 Partially loaded SLA body and set up ready for testing

The results of this series of tests revealed that the penetration performance decreased appreciably from the prior scenarios where a rocky soil overburden was used. The rocky soil portion of the overburden, which was absent from this test, was surmised to actually enhance the penetration performance of the round by providing a higher standoff, albeit through the use of a medium which proved to be relatively transparent to the shaped charge jet, allowing the jet to stretch to a more optimal length before impacting the intended target beneath.

An additional reason for the decreased penetration performance was believed to be the lack of consistent head height. The distance that the detonator is inserted into the C-4, in relation to the apex of the liner is critical to proper liner formation but was variable, subject to the depth to with which the operator inserted the detonator. As a result, the final design feature to be incorporated was the inclusion of a multi purpose tool. This tool, shaped much like a common engine valve, was used to compress the C-4 around the skirt of the liner where it was hard to reach by hand. More importantly however, when inserted through the detonator holder portion of the end cap, it was sized to provide a consistent depth for the insertion of the detonator so that the head height would not change from one shot to the next. Despite the decreased penetration performance, believed to have resulted from the lack

of standoff and variable head height, the performance was judged to be sufficient to push forward and implement all the design features on an injection molded body.

Injection molding was chosen for the production of this body for several reasons. Fragmentation was a concern since these items have to be used in populated areas and minimal fragmentation, due to concerns over collateral damage, was desired. In addition, injection molding allows parts to be produced quickly, with more than sufficient accuracy for this part, and inexpensively when compared to machining. Injection molding does however, require the purchase of a relatively expensive mold for each part which will be produced. This cost however, remains fixed in time so that as the quantities of bodies procured increases, the cost remains a relatively constant function of the price of the plastic to be used.

The injection molded body incorporated all of the design features of the earlier SLA body but in order to survive the temperature extremes that typical munitions are tested to, a much higher performance engineering plastic was required. Lexan was eventually settled on as a suitable plastic since it maintains its strength at both the high and low temperature extremes to which standard munitions are commonly tested. Although not the least expensive plastic, it was determined to be the one with sufficient properties to withstand the harsh environment of being stored and carried in an environment that typically reaches highs well over 100ºF for extended periods of time. As a final check, two final injection molded bodies were loaded and tested against live warheads. One of the final injection molded bodies, at various stages of loading, can be seen with the liner, cap, and loading/detonator seating tool in figure 9.

Figure 9 Final body with liner, end cap, and loading/detonator seating tool

The final two shots were conducted against live M107 rounds. Both shots resulted in high order detonations. Figure 10 shows the final iteration of injection molded body just before the test was conducted.

Figure 10 Final configuration setup

4. ROBOTIC DEVELOPMENT

Although this design effort focused on development of a dedicated shaped charge for use against IEDs, development efforts on the interface to the robotic manipulator proceeded in parallel and were the result of EOD personnel working in conjunction with contractors. The result of these efforts was the development of a disposable holder which houses both the shock tube and the loaded shaped charge.

The way the assembly works is the operator readies the shaped charge at a remote location, a safe distance from the IED. He then attaches the shock tube igniter and moves the robot down range to the suspected IED while maintaining the igniter at his location. As the robot moves to the IED, the shock tube pays out. The operator emplaces the shaped charge at the location of the IED and releases it with the robotic manipulator. The robot is then free to back away from both the shaped charge and the IED. The shaped charge is detonated when the robot has moved sufficiently far away. One of the nice features of the holding arm is that it was designed in such a way that after it is released, the shock tube is sufficiently outside the width of the track so that the robot will not become entangled in the line. Figure 11 is a picture of one of the robots used for this type of work, with the arm assembly, and the shaped charge.

Figure 11 Robot with remote emplacement assembly

5. SUMMARY

The disposal of UXO and IEDs is a dangerous job that has proven quite costly for U.S. military personnel. As a result, U.S. Army EOD operators have been forced to devise new methods of safely disposing of or destroying these devices. One method that they've devised is to remotely emplace a shaped charge via robot. This method allows the operator to stand a safe distance away from the IED while setting up a device capable of destroying explosive ordnance. Up until now however, although shaped charges existed for the purposed of destroying exposed explosive ordnance, none were available that could penetrate a significant amount of asphalt and soil overburden, the scenario that IEDs are commonly encountered in, before setting off a buried device. Warheads development personnel, working in conjunction with EOD operators designed and developed a dedicated plastic bodied shaped charge that was not only sufficient to penetrate at least a half of a foot of asphalt and an equal amount of rocky soil before setting off ordnance buried below, but one which was small and light enough to be deployed via a robotic manipulator.

This device, developed, tested and fielded within just 8 months, was designed to be loaded by the user in the field with Composition C-4. It incorporates a copper liner for high performance, a minimally fragmenting plastic body with a built in stand off, a roll resistant lid, and a detonator seating tool. Used in conjunction with a recently designed emplacement assembly and one of a variety of remotely controlled robots, it represents a solution to the problem of destroying buried IEDs which did not previously exist.

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Outline

- Background – problems and solutions
- Fundamental shaped charge-explosive relationships
- Shaped charge modeling
- Prototype test setup and results
- Subsequent testing and results
- Locally fabricated parts and the final design
- Robotic assembly
- Acknowledgements

Background - Problem

Large stockpiles of UXO readily used for IEDs

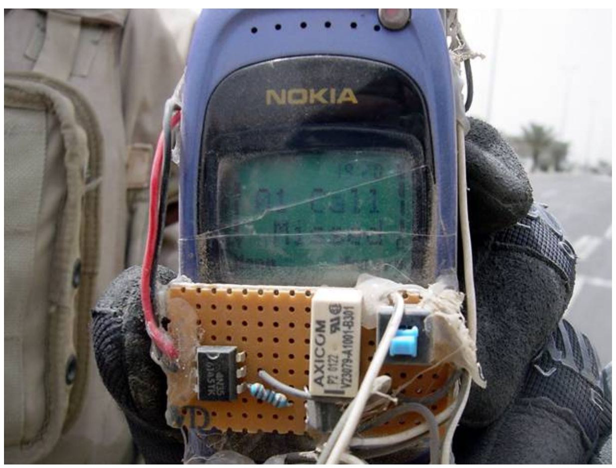
Background - Problem

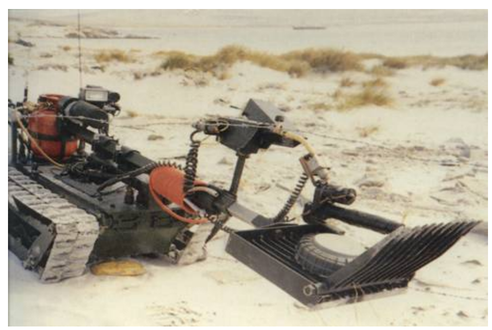
Tremendous cost – Personnel and Materiel

Background – Traditional Solutions

Traditional UXO/IED disposal methods are time consuming and dangerous and useful for exposed/unmonitored ordnance

Background – Newer Solutions





Active insurgent tactics/terrain dictate alternative handling

Background Summary

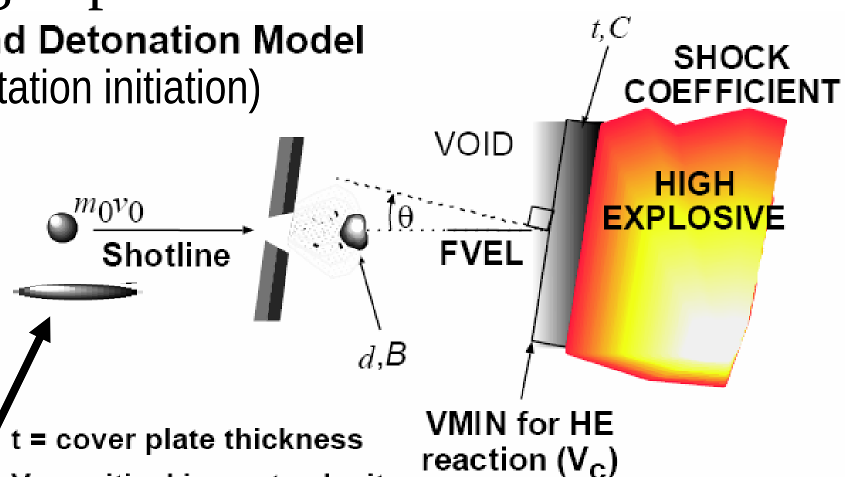
- Buried IEDs with observation and command detonation necessitate remote destruction
- Bulk explosives typically used for destruction of uncovered ordnance effective but limited
- Minimal fragmentation desirable for urbanized terrain
- Current counter ordnance shaped charges are relatively low precision/performance
- Precise penetration through greater overburden was needed quickly

Shaped Charge IED Defeat

- Shaped charges provide the highest penetration of all munitions (over 8X their diameter into steel)
- Shaped charges are extremely efficient at initiation.
- Initiation of explosives by impact is controlled by the impact velocity squared and projectile diameter
- Shaped charge jets have extremely high velocities, so they are efficient at initiating explosives

Jacobs-Roslund Detonation Model
(for fragmentation initiation)

$$v_c = \frac{A}{\sqrt{d(TH)}}(1+B)\left(1+C\frac{t}{d}\right)$$



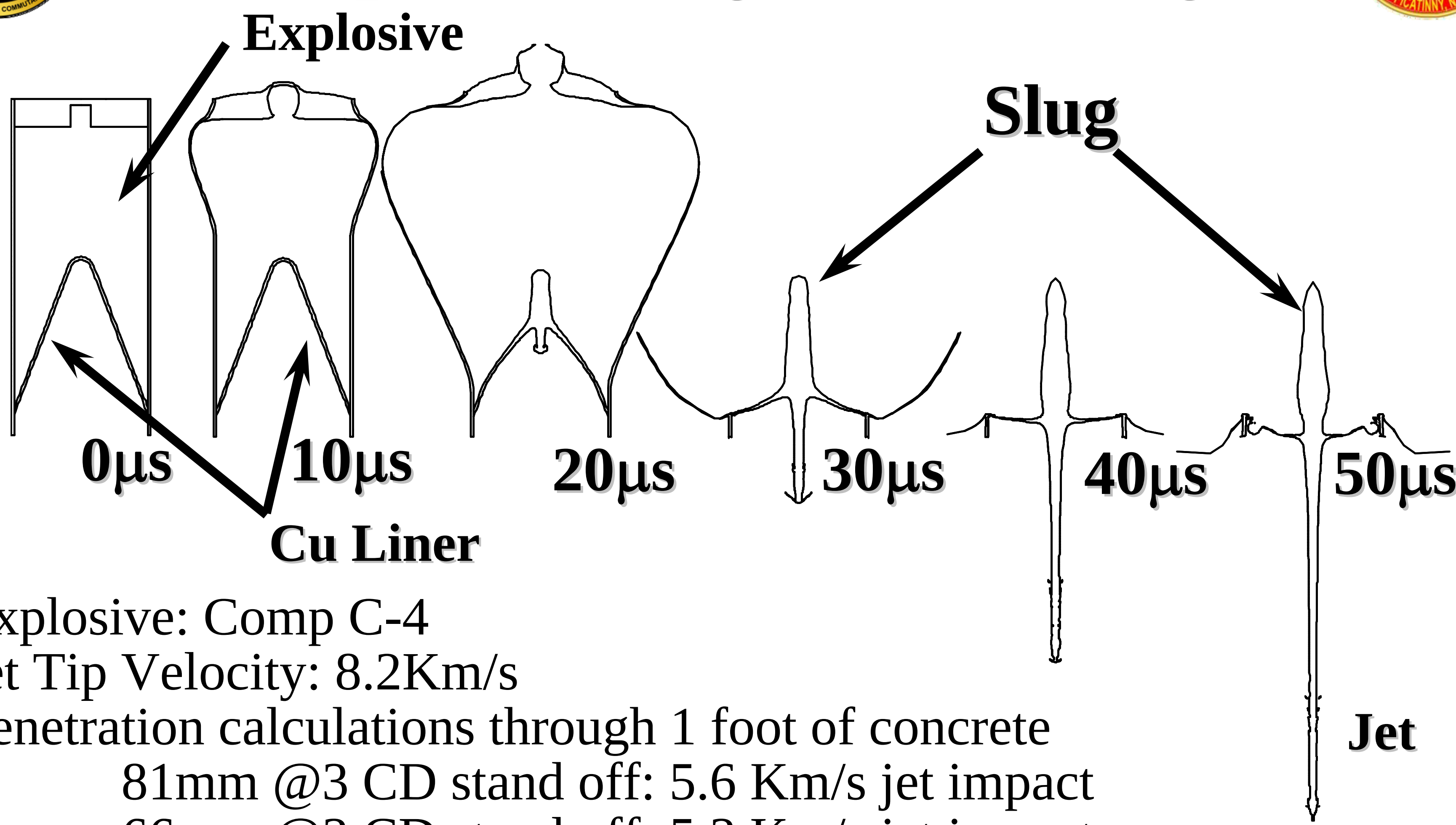
Where:

- A = explosive sensitivity coefficient
- C = cover material constant
- d = projectile diameter
- TH = cos(θ)
- B = projectile shape constant
- t = cover plate thickness
- V_c = critical impact velocity

Held's Criteria
(for shaped charge jets)

$$v_c^2 d = \text{constant}$$

Shaped Charge Modeling



Explosive: Comp C-4
Jet Tip Velocity: 8.2Km/s
Penetration calculations through 1 foot of concrete

81mm @3 CD stand off: 5.6 Km/s jet impact
66mm @3 CD stand off: 5.3 Km/s jet impact
81mm @1 CD stand off: 4.1 Km/s jet impact
66mm @1 CD stand off: 3.9 Km/s jet impact
(CD=Charge Diameter …*the shaped charge diameter*)

Extremely High Velocities!

Initial Prototypes

Unloaded prototypes

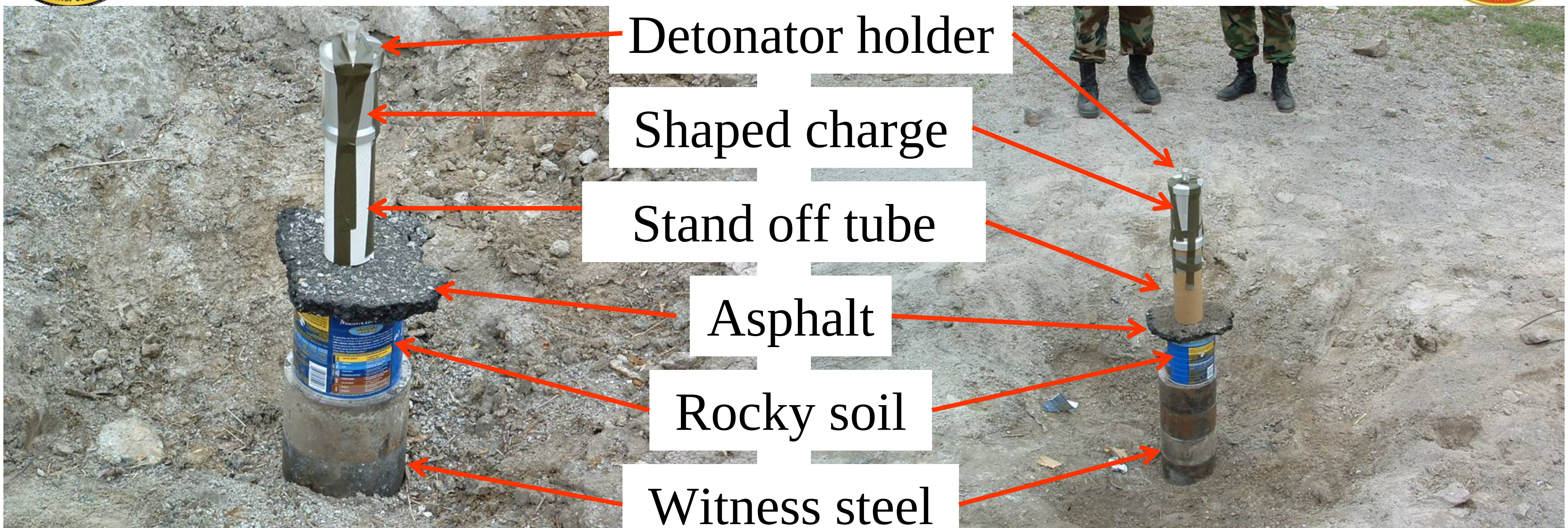
81 mm

66 mm

Prototype loading

Charges hand loaded with Comp C-4 explosive

Prototype Setup



66mm @3 CDs stand off

81mm @3 CDs stand off

- 2 Sizes of Cu shaped charges tested: 81 mm & 66 mm
- 2 Stand off distances tested: 1 CD & 3 CDs (charge diameters)
- Overburden requirement
  - testing through asphalt, dirt and high velocity penetration of metal (into projectile)
  - assure IED defeat under worst case conditions
  - dictated by operators recently returned from the field

Prototype Results

66 mm at 3 CDs stand off

66 mm at 1 CD stand off

81 mm at 1 CD stand off
(CD=Charge Diameter)

66mm charge proved to be more than adequate

Subsequent Testing

Shot 1

Shot 2

- 66mm charge was verified to be sufficient
- Settled on 1 CD of stand off for performance and stability
- Testing against live M107 artillery projectiles as representative IED samples
- Additional steel used as extra overburden for a more difficult test

Subsequent Testing - Results

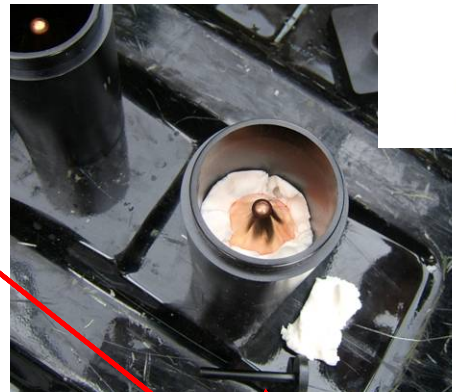
Shot 1- high order detonation

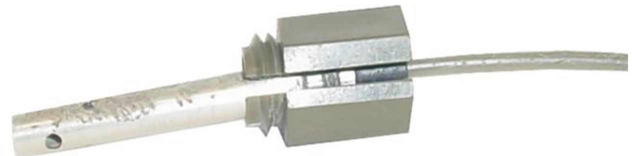
Shot 2- destroyed beyond use
(not high order)

Local Production Prototypes

- Stereo Lithography Apparatus (SLA) bodies produced by EOD personnel
- Allowed rapid incorporation of design improvements
  - 1 way assembly
  - Anti-roll interference fit lid
  - Built in standoff
- Design determined to be sufficient for injection molding

Final Design and Testing





Detonator adapter

Completed assembly

Loading tool

Final design features:

- Injection molded
- Standard detonator holder to ensure consistent maximum head height
- C-4 packing tool to assist with packing to ensure better HE to liner interface and head height
- Lexan chosen due to requirements to operate under environmental extremes

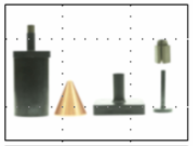
Final Tests

Both rounds detonated high order!

Final Design "Soldierized"

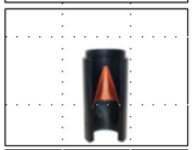
Assembly Instruction for 66MM Plastic Shape Charge Assembly(PSCA)

Introduction: The PSCA is an on-the-spot assembled shape charge assembly used to defeat IEDs. It consists of the pusher rod, MDI adapter, cap, body and copper liner.



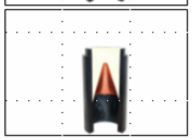
Assembly Instruction:

Step 1: Place copper liner into body cavity. The cone should rest evenly on the inside protruding lip.



Step 1

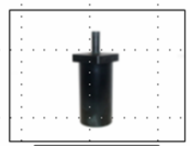
Step 2: Pack C4 into body cavity tightly and the copper liner should stay even and not cocked. The packed C4 shall be flushed to the top of the plastic housing and not above. The weight of the packed C4 is about 0.90 lb.



Step 2

Assembly Instruction for 66MM Plastic Shape Charge Assembly(PSCA)

Step 3: Close cap on body tightly. There should be no gap between the cap and the housing.

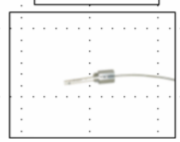


Step 3

Step 4: Insert push rod into cap and seat fully to create maximum MDI detonator depth.

Step 4

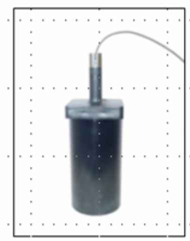
Step 5: Position MDI detonator into MDI adapter.



Step 5

Assembly Instruction for 66MM Plastic Shape Charge Assembly(PSCA)

Step 6: Thread MDI adapter with MDI detonator into cap and seat fully. The MDI detonator should be pushed down until resistance is felt. In the absence of MDI adapter, just insert MDI detonator fully into cap until resistance is felt and secured tightly to cap with tape. Warning: Do not exceed pushrod depth when inserting detonator, the shape charge will not form properly and the detonator will be pushed into the tip of the copper cone.

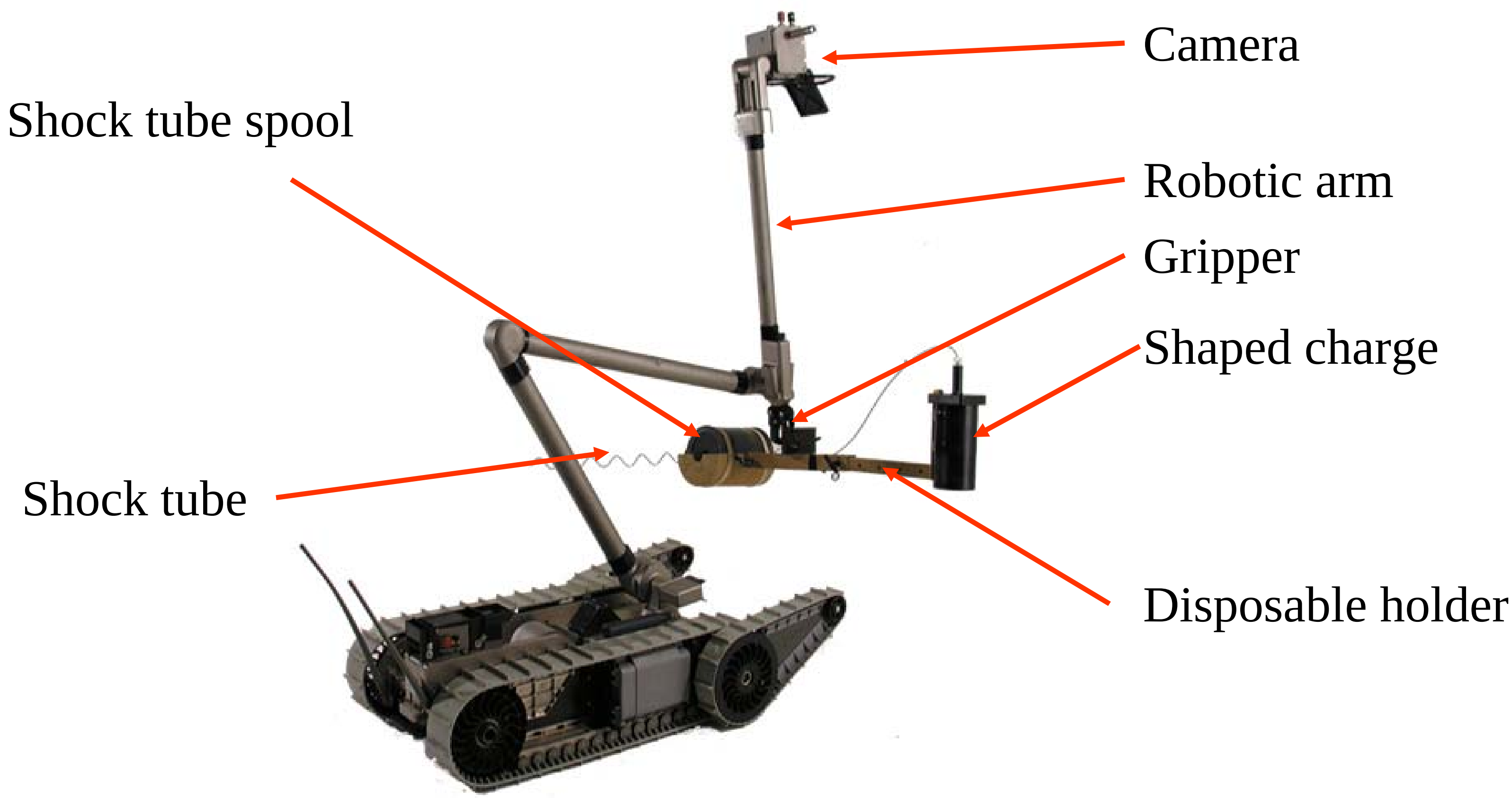


Step 6

Step 7: PSCA is ready to be deployed.

Instruction set

Robotic Emplacement Assembly



- EOD personnel codesigned the arm with STS for robotic emplacement
- The adjustable arm is wider than the robot to stop snagging on the tracks
- The shaped charge and holder assembly is carried down range where it is dropped and the robot backed away

Assembled and fielded *within 8 months* of initial testing!

SFC Scott Smith

Died in Iraq as a result of injuries sustained after an IED he was working on detonated

Questions ?